A Novel Global MPPT Algorithm for Distributed MPPT Systems

Stefan Daraban[1], Dorin Petreus[1], Cristina Morel[2], Mohamed Machmoum[3]
[1]Technical University of Cluj-Napoca, 26-28 St. G. Baritiu, 400027 Cluj-Napoca, Romania
[2]ESEO, 10 Bd. Jeanneteau, 49107 Angers, France
[3]IREENA, 37 Bd. de l'université BP 406, 44602 Saint-Nazaire, France
E-Mail: stefan.daraban@ael.utcluj.ro

Acknowledgements

This work was supported by the project INNOWECS CNCS–UEFISCDI, project no. PN-II-PT-PCCA -2011-3.2-1696.

Keywords

Photovoltaic, Converter control, DSP, Renewable energy systems, DC power supply.

Abstract

This paper is focused on the implementation of an original algorithm for global maximum power point tracking (GMPPT) in photovoltaic systems. The algorithm detects when partial shading occurs, thus eliminating unwanted voltage sweeping. The paper gives a detailed analysis on how the algorithm succeeds in finding the global maximum power point (GMPP) in a short time and all its highlights. The system is controlled by a DSP which implements a voltage and a current loop for a better response of the system in case of a luminosity step change. Simulation and experimental results are finally provided to verify the performance of the system.

Introduction

Photovoltaic energy is a big competitor on the renewable energy market. In order to obtain the best efficiency from this kind of system, the appropriate control method, power topology and maximum power point tracking (MPPT) algorithm must be used. In a photovoltaic panel the solar cells are stacked together in order to raise the output voltage and these strings are connected in parallel to raise the output power.

An important phenomenon that reduces energy harvesting in photovoltaic applications is the partial shading effect. The cell with the lowest irradiance determines the current through the whole series string. In order to assure the string current, bypass diodes are connected in parallel with solar panels which get shunted when they are shaded.

In [1] an experiment was carried to test different maximum power point (MPP) trackers that were on the market. The experiment was carried out on 13 trackers from different producers. All of these trackers succeeded in tracking the MPP for a solar panel which was not affected by partial shading. Only 7 managed to track the MPP when two maxima were present and none of them managed to find the GMPP when three maxima were present on the characteristic. The experiment showed that 70% power was lost because the GMPP was not found for some of the tested characteristics, thus proving the necessity of developing algorithms that can track the global maximum power point for a string of PV modules affected by shading.

There are many methods described in the literature that treat the MPPT algorithms for strings of panels under the influence of partial shading. These algorithms concentrate very much on finding the global maximum power point and very few treat the problem of partial shading identification. There can be situations when the characteristic is not affected by shadowing and the MPPT algorithm starts sweeping the input voltage in order to find the global maximum power point. In [2] the author proposes a method to identify global partial shading.

When dealing with partial shading and local MPP, the only way to get out of a valley located on a P-V characteristic is to sweep the characteristic. The first algorithms that concentrated on characteristics with multiple maxima were sweeping the entire input voltage with some boundaries in order to avoid under voltage lockout of the inverter. These kinds of algorithms were treated in [2].

An improvement was to combine tracking (local MPP) and scanning (global MPP), [3-4]. After a local MPP is found a jump is made to the next area on the characteristic that presents a local MPP. The jump is made with a fixed voltage that is calculated with some parameters obtained from the datasheet of the PV module, [3]. The scanning period has to be small enough to avoid energy loss. The scanning can be triggered by a sudden change of power or by a partial shading identification method.

Some artificial intelligent techniques were proposed in order to find the GMPP. A Fibonacci search based algorithm was proposed in [5], and a fuzzy algorithm was proposed in [6]. Particle swarm optimization can be applied to this kind of algorithms for a faster tracking of the GMPP [7]. In [8] the authors proposed a tracking method based on genetic algorithms (GA). The results show that the solution given by the GA reaches the GMPP. The disadvantage with algorithm based on artificial intelligence is that sometimes they take too much to find a solution especially if the string voltage is very high.

Partial Shading Phenomenon

The current voltage (I-V) characteristic of a solar cell for the whole voltage range is represented in Fig. 1. This figure shows what happens when solar cells with different short circuit currents (I_{sc}) or irradiance levels are connected in series or solar cells with different open circuit voltage (V_{OC}) or different temperatures are connected in parallel. The upper marked region shows the mismatch series connection and the lower marked region shows the mismatch parallel connection. In both cases, the solar cells absorb power from the good cells and dissipate it as heat. If this power is not controlled or the reverse voltage on the junction is not lowered, the junction breaks down and the hot spot effect appears, leading to cracks in the solar panel and permanent damage. Hot spot effect appears due to large concentrated currents through the cell, [9].

All PV modules have to comply with the IEC 61215 standard to pass the hot-spot endurance test. A solution to prevent hot spot effect is to integrate bypass diodes into the solar panel, thus limiting the reverse voltage of the shadowed solar cells. When there is no partial shading, the bypass diode has no effect on the circuit. When a solar cell is shaded, the bypass diode limits the voltage to:

$$V_{reverse} = m \cdot V_{OC} + V_{Bdiode} \tag{1}$$

where $V_{reverse}$ is the reverse voltage drop on the shadowed cell, m is the number of cells which are not shadowed from the group of bypassed cells, V_{OC} is the open circuit voltage of single solar cell and V_{Bdiode} is the voltage drop of a bypass diode.

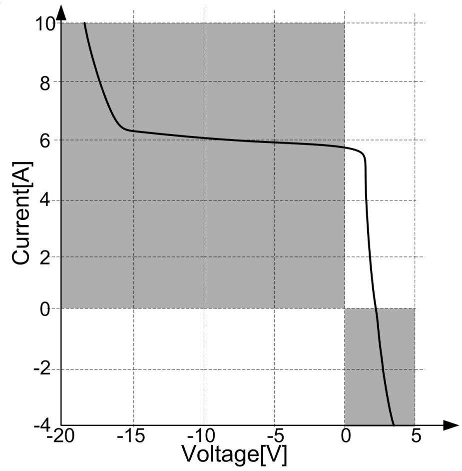


Fig. 1. Full I-V characteristic of a solar cell.

In order to protect the solar cell from the hot spot effect or to improve power extraction, different bypass diodes configurations, [9], and solar cell configurations have been developed, [10].

Fault tolerance to mismatch conditions has been achieved with bypass diodes. The bypass diode configurations are presented in [9], Fig. 2. There are two kinds of bypass diode: not overlapped and overlapped. The non overlapped connection, Fig. 2a), makes the analysis of the circuit simple because it divides a string of cells in smaller groups and the equations are easy to write. The overlapped connection, Fig. 2b), makes the analysis of the circuit a little harder because the system has to be treated unitarily and the diodes introduce additional connection in between strings. In [9], the authors conclude that is better to use non overlapped bypass diodes because the power efficiency of the system is better and more energy can be harvested in this way.

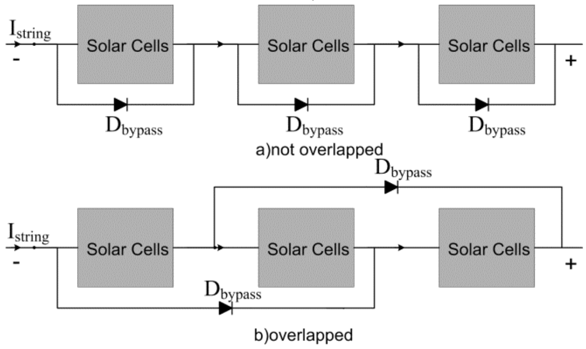


Fig. 2 Bypass diode configuration.

The block "Solar Cells" from Fig. 2 can be replaced with a topology from Fig. 3. The solar cells are connected in series, Fig. 3a), in order to raise the PV voltage and in parallel, Fig. 3b), in order to raise the output current. The right topology connection between solar cells/panels can improve the power harvesting with 4%, [10]. The TCT, Fig. 3c), and BL, Fig. 3d), topologies introduce additional connections which create multiple paths for the current. The BL topology has half the interconnections of a TCT topology. Choosing a good topology for interconnecting solar cells slows the aging process of a solar cell, [11]. Some power plants incorporate PV array reconfiguration strategies that measure the irradiance of panels and change the interconnections between PV modules, in order to minimize the mismatch irradiance between them and improve energy harvesting, [12]. By introducing bypass diodes in a solar panel multiple maxima are obtained.

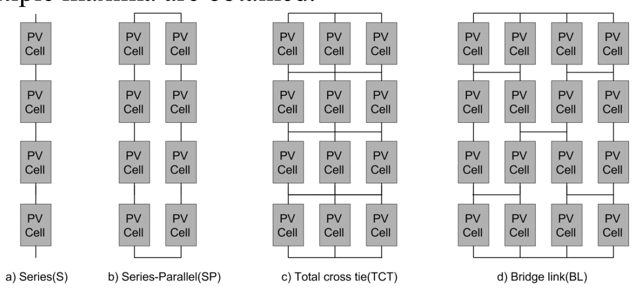


Fig. 3 Solar cell/panel array topologies.

GMPPT Algorithm

In this section a solution for finding the MPP under partial shading is presented. This method of finding the GMPP is based on detecting when a partial shading condition occurs, thus eliminating unwanted characteristic scans. The scanning of the P-V characteristic leads to power loss and takes a lot of time. A method is proposed to search local MPP (LMPP) without scanning all the points in the solar panel's characteristic. From all the LMPP the one with the highest power is set as the new operating point.

The characteristic of a string of solar panels affected by partial shading, which uses bypass diodes, is presented in Fig. 4. The characteristic presents multiple maxima equal to the number of shaded panels. If the bypass diodes are replaced with power converters the characteristic will have a single maxima and the extracted output power will increase. This system is called distributed MPPT

(DMPPT). There is a recent trend in photovoltaic applications that replaces the bypass diodes with power converters, thus eliminating local MPP (LMPP). This concept is named distributed MPPT (DMPPT). Some DMPPT concepts described in the literature are: PV voltage equalization [13], series connected DMPPT [14], parallel connected DMPPT [15], differential power processing [16] and microinverters [17]. The PV modules have bypass diodes connected inside for protecting the cells from mismatch conditions. A GMPPT algorithm is proposed in order to improve energy extraction on each solar panel.

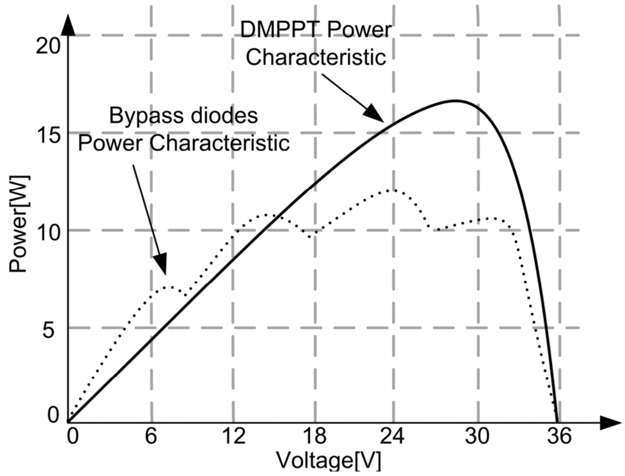


Fig. 4 P-V characteristic with partial shadowing.

Certain parameters can be found in the datasheet of solar panel: V_{mpp}, I_{mpp}, V_{OC}, I_{SC}, $coefI_{SC}$, $coefV_{OC}$. The parameters $coefI_{SC}$ and $coefV_{OC}$ are the temperature coefficients of I_{SC} and V_{OC}. For detecting partial shading conditions is enough to check that the voltage of the tracked MPP is bigger than the V_{mpp} given in the datasheet. This condition will give false results in case the temperature of the solar panel changes. The locus of the MPP will be calculated next, as a function of parameters that depend on the temperature. The equation of the locus will permit to find a partial shading condition.

The equation of a solar panel with n solar panels connected in series is:

$$I_{PV} = I_{ph} - I_s\left[\exp\left(\frac{V_{PV} + I_{PV}\cdot R_S}{n\cdot V_T}\right) - 1\right] - \frac{V_{PV} - I_{PV}\cdot R_S}{R_{sh}} \quad (2)$$

where I_{PV} is the output current of the solar panel, V_{PV} is the voltage of the panel, R_S is the series resistance of the solar panel, R_{sh} is the parallel resistance of the panel, I_{ph} ($I_{sc}\cdot S/S_0$) is the short circuit current as a function of its irradiance, V_T is the thermal voltage of a semiconductor p-n junction and I_S is the reverse bias saturation current of the diode. By using $R_S=0$ and $R_{sh}=\infty$ in (2) the calculations can be simplified and also obtain good results.

The output power of a solar panel can be written as:

$$P_{in} = V_{PV}\left\{I_{ph} - I_s\left[\exp\left(\frac{V_{PV}}{n\cdot V_T}\right) - 1\right]\right\} \quad (3)$$

The derivative of the P-V characteristic is:

$$\frac{\partial P_{PV}}{\partial V_{PV}} = \frac{\partial\left\{V_{PV}\cdot I_{ph} - V_{PV}\cdot I_s\left[\exp\left(\frac{V_{PV}}{n\cdot V_T}\right) - 1\right]\right\}}{\partial V_{PV}} \quad (4)$$

In order to obtain the MPP value, the derivative of the output power must satisfy:

$$\frac{\partial P_{PV}}{\partial V_{PV}} = 0 \qquad (5)$$

From (4) and (5) the following equation is obtained:

$$I_{ph} = I_s \left[\exp\left(\frac{V_{MPP}}{n \cdot V_T} \right) - 1 \right] + \frac{I_s \cdot V_{MPP} \cdot \exp\left(\frac{V_{MPP}}{n \cdot V_T} \right)}{n \cdot V_T} \qquad (6)$$

where V_{MPP} is the MPP voltage.

Using (6) in the simplified form of (2), one can obtain the locus of the I_{MPP}:

$$I_{MPP} = \frac{I_s \cdot V_{MPP} \cdot \exp\left(\frac{V_{MPP}}{n \cdot V_T} \right)}{n \cdot V_T} \qquad (7)$$

The MPP locus is obtained by replacing (7) in (3):

$$P_{MPP} = V_{MPP} \cdot I_{MPP} = \frac{I_s \cdot V_{MPP}^2 \cdot \exp\left(\frac{V_{MPP}}{n \cdot V_T} \right)}{n \cdot V_T} \qquad (8)$$

In Fig. 5 one solar panel is unshaded and the other panels are partially shaded with different luminosities. It can be seen that the shading on the panels cuts slices from their P-V characteristics and places the local maximum power point at the right side of the MPP of a fully irradiated P-V characteristic.

The locus of the MPP is also represented in Fig. 5. The proposed algorithm that finds the global MPP under partial shadowing is based on the observations from this figure. It can be seen that the MPP affected by partial shading is at the right side of the MPP locus unaffected by shadowing. The MPP is found by a P&O algorithm. The voltage of the tracked operating point is replaced in (8). If the power of the tracked MPP is much smaller than the power obtained by (8), this means that partial shading occurred.

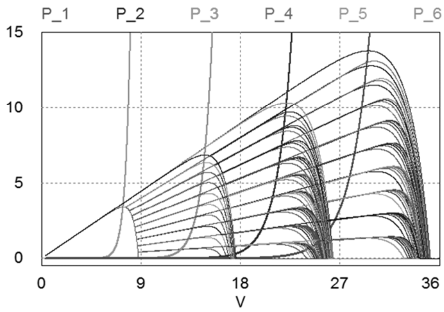


Fig. 5 Characteristics of the MPP locus.

The main idea of the proposed algorithm is to search the local MPP with a P&O. In case of partial shadowing, after a local MPP is found, a jump will be made to a fixed location given by (9). The jump assures fast tracking and little energy loss during the searching. All local MPP will be searched and then from these values the global MPP will be set as the next operating point. The discrete steps that the algorithm does, after finding a local MPP, place the operating point very close to the next local maximum power point. The jump size is justified in Fig. 5. It can be seen that the MPP of a shadeless characteristic is very close to the MPP of a shaded characteristic. After a jump at $i \cdot V_{MPP}$, in a few steps the local MPP is found.

$$V_{MPP\_i} = i \cdot V_{MPP} \tag{9}$$

where i is the i[th] panel in the string.

An original property of the proposed GMPPT algorithm is that it searches to see if the shading effect disappears as shaded panels get bypassed while decreasing the voltage on the string PV module. If the shading phenomenon disappears for the remaining panels, the LMPP for these PV modules will be set at the operating point where the above condition was first met. In this way energy will be saved and the GMPPT will be tracked faster.

Next, the values of I_S and V_T will be computed in order for their values to be used in (8). The short circuit current and the open circuit voltage vary according to their temperature coefficient:

$$I_{SC} = I_{SC0} + (T_{panel} - T_{amb}) \cdot I_{SC0} \cdot coefI_{SC} \tag{10}$$

$$V_{OC} = V_{OC0} + (T_{panel} - T_{amb}) \cdot V_{OC0} \cdot coefV_{OC} \tag{11}$$

where I_{SC0} and V_{SC0} are the short circuit current and open circuit voltage at T_{amb}, T_{panel} is the temperature on the solar panel, T_{amb} is the temperature which was considered when the measurements were taken.

By making equal the simplified form of (2) with (7) and rearranging the result, one can obtain:

$$1 + \frac{I_{SC}}{I_S} = \exp\left(\frac{V_{MPP}}{n \cdot V_T}\right) \cdot \left(1 + \frac{V_{MPP}}{n \cdot V_T}\right) \tag{12}$$

Applying a logarithmic function to (12) the following equation is obtained:

$$\ln\left(1 + \frac{I_{SC}}{I_S}\right) = \frac{V_{MPP}}{n \cdot V_T} + \ln\left(1 + \frac{V_{MPP}}{n \cdot V_T}\right) \tag{13}$$

In (2) if the open circuit condition is applied, then one can obtain:

$$\ln\left(1 + \frac{I_{SC}}{I_S}\right) = \frac{V_{OC}}{n \cdot V_T} \tag{14}$$

Applying (14) in (13) a transcendent function is obtained from which the V_T value can be obtained by using an iterative algorithm inside the processor:

$$\frac{V_{OC} - V_{MPP}}{n \cdot V_T} = \log\left(1 + \frac{V_{MPP}}{n \cdot V_T}\right) \tag{15}$$

The saturation current of the diode can be calculated with:

$$I_S = \frac{I_{SC}}{\exp\left(\frac{V_{OC}}{V_T}\right) - 1} \tag{16}$$

In order to improve the response of the system to luminosity step change, the GMPPT algorithm is helped by the control loops of the converter. The MPPT algorithm represents a power loop which gives the reference for the voltage loop. The voltage loop gives the reference for the current loop. The advantage of having two control loops improves the stability of the system and eases the compensation process, [18]. The current and voltage loop of the converter were implemented inside the DSP.

The locus of the MPP is calculated in the MPPT controller according to (8). After applying the shadowing detection method a MPPT algorithm is used to track the local MPP. In the next section the simulation and experimental results will be presented to prove the performance of the proposed GMPPT algorithm.

Simulation Results

A small scale system was developed in order to test this algorithm. This principle can also be applied to systems that have a higher voltage and a higher power. The panel was modeled with current sources in parallel with diodes. It was also included a series resistance and parallel resistance on the panels. A bypass diode was mounted on each model in order to ensure current flow into the string when partial shading occurs.

The string has a total number of four panels connected in series, thus meaning a number of four LMPP can be found. A buck converter is connected to the panel for extracting the energy. Because the output voltage of the panel is 12V, the lowest LMPP can not be tracked and only a total number of three local MPP will be searched.

This system is similar with a distributed MPPT placed on a single panel. The MPP on a PV module in a DMPPT system is searched independently from the other solar panels in the system. The panel itself incorporates bypass diodes thus meaning in case of partial shading the panel presents multiple LMPP.

The schematic of the system is presented in Fig. 6. At the input of the converter there are four strings of PV cells connected in series giving a maximum V_{OC} of 34V. The short circuit current is varied between 200mA and 500mA. The inductor has a value of 23µH, the input capacitor is 1mF and at the output a 12V lead acid battery is connected.

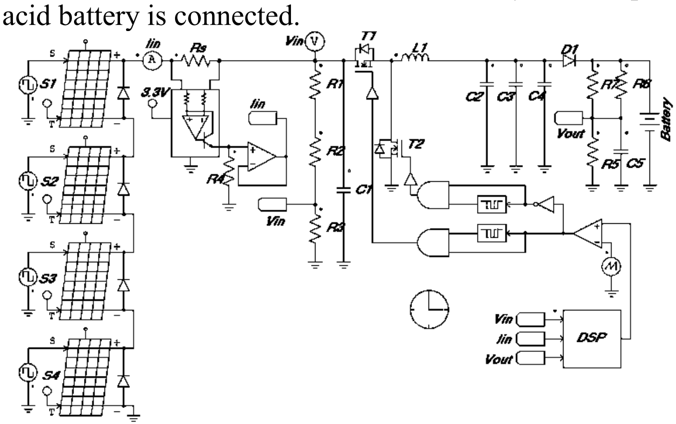


Fig. 6 Schematic of the system.

The shading patterns on which the algorithm will be applied are presented in Fig. 7. Each characteristic of the solar panel was chosen in order to highlight a certain feature of the algorithm. The characteristic from Fig. 7a) will indicates how the algorithm detects a shading condition and searches the LMPP and from these operating points it settles on the one with the highest power. When the panel is fully irradiated the system detects that partial shading has not occurred and does not sweep the string voltage.

It can be seen in Fig. 7b) that there are two irradiance levels, thus there are two local MPP. It can be seen that when the algorithm tries to track the third local MPP (which is located at a voltage close to $3\cdot(V_{MPP}/n)$ it quickly realizes that there is no third peak and continues to track the next maxima. The algorithm realized that there was no third peak when it crossed over the $3\cdot(V_{OC}/n)$ threshold voltage. If this condition was not imposed the algorithm would close itself into a continuous loop or would lose time tracking the same LMPP.

The third P-V characteristic, Fig. 7c), will shows that the algorithm is able to recognize when the shading is no longer present for the remaining PV modules, thus eliminating undesired long jumps. In this context, shading disappearance means that the remaining solar panels do not present mismatch conditions and there are no more LMPP.

Simulation results will be presented next. The irradiance step change occurs once every second. The power extracted from the panels is illustrated bellow the voltage and current waveforms. It can be

 ISBN: 978-90-75815-17-7 and 978-1-4799-0114-2

seen from the simulations that after a step luminosity change, the algorithm finds the GMPP and sets this values as the new operating point.

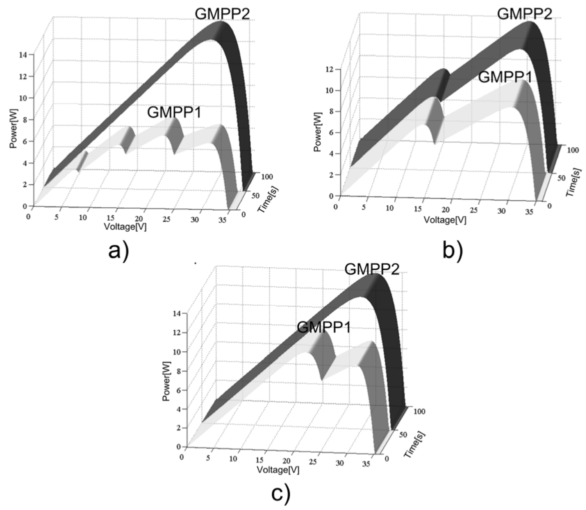


Fig. 7 Shading patterns to the proposed GMPPT algorithm.

Simulation results for the first pattern are presented in Fig. 8a), for the second pattern in Fig. 8b) and for the third patter in Fig. 8c).

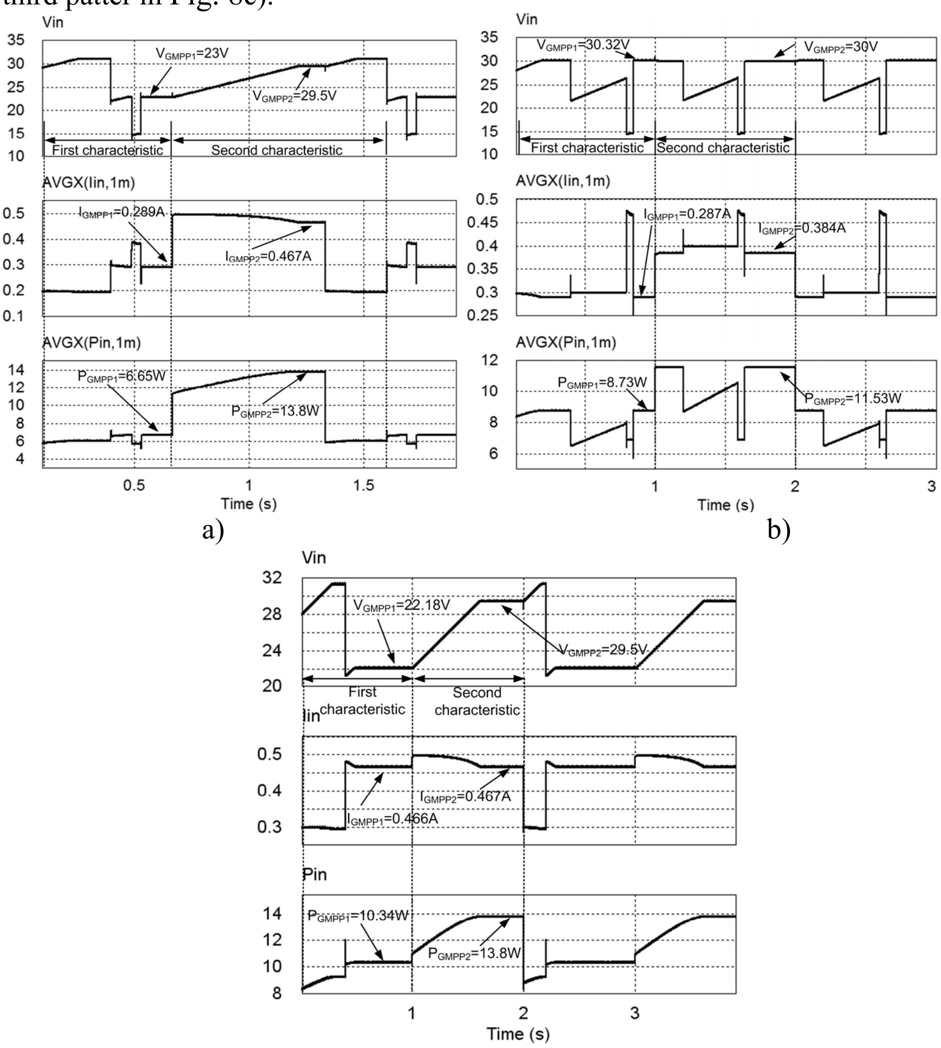
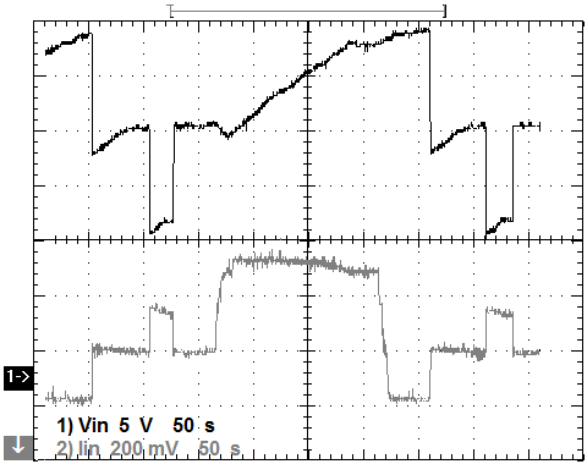


Fig. 8 Simulations of the system for: a) the first pattern; b) the second pattern; c) the third pattern

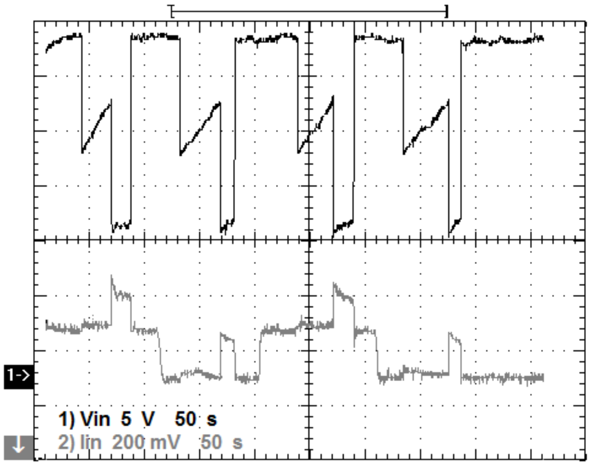
Experimental Results

Experimental results will be presented next. For the first shading pattern, presented in Fig. 7a), the algorithm identifies that a partial shading condition occurred and starts searching all LMPP, Fig. 9a). From the characteristic, simulation and experimental results it can be concluded that the third LMPP gives the maximum power for this irradiation. A luminosity step change is applied and there is no more partial shading. The algorithm detects this condition and settles on the fourth LMPP. The process repeats itself.

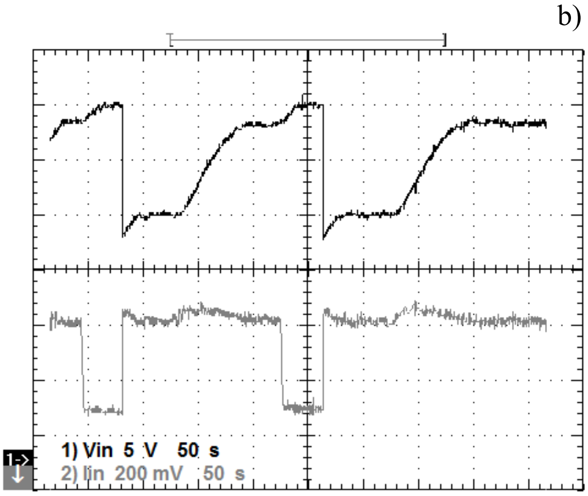
Experimental results for the second pattern are provided in Fig. 9b). It can be seen that the experimental results are similar with the simulation results from Fig. 8b). Energy was saved during the tracking of the third LMPP. The algorithm realized that this operating point does not exist and proceeded with the searching of the next LMPP. The experimental results for the third shading pattern are presented in Fig. 9c). It can be seen that the algorithm identifies when the shading condition disappears and does not look for other LMPP.



a)



b)



c)

Fig. 9 Experimental results of the system for: a) the first pattern; b) the second pattern; c) the third pattern.

Conclusions

This paper proposes a global maximum power point tracking algorithm for searching the optimum operating point of a PV panel under the influence of partial shading.

This algorithm can be applied to central inverters and also to DMPPT systems. The highlights of this algorithm are: finding the GMPP without scanning the whole characteristic, it takes into account the temperature on the solar panel, detects when partial shading occurs and when this phenomenon disappears. The performance of the algorithm was tested with simulation and experimental results.

References

[1] R. Bruendlinger, B. Bletterie, M. Milde and H. Oldenkamp, “Maximum power point tracking performance under partial shaded PV array conditions” European Photovoltaic Solar Energy Conference, pp. 2157-2160, Dresden, Germany, September 2006

[2] Y. Liu, “Advanced control of photovoltaic converters”, PhD theses, University of Leicester, England, April 2009

[3] C.L. Nge, G. Yordanov, O.M. Midtgard, T.O. Sætre and L. Norum, “A comparative simulation analysis of maximum power point tracking approaches,” 24th Eur. Photovoltaic Solar Energy Conference, Hamburg, Germany, September 2009

[4] Y.H. Ji, D.Y. Jung, J.G. Kim and J.H. Kim, “A real maximum power point tracking method for mismatching compensation in PV array under partially shaded conditions”, IEEE TPE, vol. 26, pp. 1001-1009, 2011

[5] M. Miyatake, H. Zhao, H. Otsuka, I. Chino, T. Kadowaki and M. Nakano. “Response of Fibonacci search based maximum power point tracker when a photovoltaic array is partially shaded,” EuroPES Conf., 2003.

[6]B.N. Alajmi, K.H. Ahmed, S.J. Finney and B.W. Williams “A maximum power point tracking technique for partially shaded photovoltaic systems in microgrids,” TIE, vol. 60(4), pp. 1596-1606, 2013

[7] K. Ishaque, Z. Salam, M. Amjad and S. Mekhilef, “An improved particle swarm optimization (PSO)–based MPPT for PV with reduced steady-state oscillation,” TPE, vol. 27(8), pp. 3627-3638, 2012

[8] R. Ramaprabha and B.L. Mathur, “Genetic algorithm based maximum power point tracking for shaded solar photovoltaic array,” International Journal of Research and Reviews in Information Science, vol. 2(1), 2012

[9] E. Díaz-Dorado, A. Suárez-García, C. Carrilo and J. Cidras , “Influence of the shadows in photovoltaic systems with different configurations of bypass diodes,” Int. Symp. on Power Elect. Electrical Drives Auto. and Motion, Pisa, Italy, June 2010

[10] D. Picault, B. Raison, S. Bacha, J. de la Casa and J. Aguilera, “Forecasting photovoltaic array power production subject to mismatch losses,” Solar Energy, vol. 84, pp. 1301-1309, 2010

[11] N.D. Kaushika and A.K. Rai, “An investigation of mismatch losses in solar photovoltaic cell networks,” Energy, vol. 32, pp. 755-759, 2007

[12] G.V. Quesada, F.G. Gispert, R.P. Lopez and R.M. Lumbreras, “Electrical PV aray reconfiguration strategy for energy extraction improvement in grid-connnected PV systems,” IEEE Transactions on Industrial Electronics, vol. 56, no. 11, pp. 4319-4331, 2009.

[13] L.F.L. Villa, T.P. Ho, J.C. Crebier, and B. Raison “A power electronics equalizer application for partially shaded photovoltaic modules,” IEEE Transactions on Industrial Electronics, vol. 60(2), pp. 1179-1190, 2013

[14] R.C.N. Pilawa-Podgurski, and D.J. Perreault, “Submodule integrated distributed maximum power point tracking for solar photovoltaic applications,” IEEE TPE, vol. 28(6), pp. 2957-2967, 2013

[15] K.C. Tseng, C.C. Huang and W.Y. Shih, “A high step-up converter with a voltage multiplier module for a photovoltaic system,” IEEE Transactions on Power Electronics, vol. 28(6), pp. 3047-3057, 2013

[16] P.S. Shenoy, K.A. Kim, B.B. Johnson and P.T. Krein, “Differential power processing for increased energy production and reliability of photovoltaic systems,” IEEE Transactions on Power Electronics, vol. 28(6), pp. 2968-2979, 2013

[17] D. Petreus, S. Daraban, I. Ciocan, T. Patarau, C. Morel and M. Machmoum, “Low cost single stage micro-inverter with mppt for grid connected applications”, Solar Energy, vol. 92, pp. 241-255, 2013

[18] D. Petreus, T. Patarau, S. Daraban, C. Morel and B. Morley, “A novel maximum power point tracker based on analog and digital control loops,” Solar Energy, vol. 85, 2011